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# The possibility of a self-gravitating disc around L1527 IRS?

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## ABSTRACT

Recent observations of the Class 0 protostar L1527 IRS have revealed a rotationally supported disc with an outer radius of at least 100 au. Measurements of the integrated flux at 870  $\mu\text{m}$  suggest a disc mass that is too low for gravitational instability to govern angular momentum transport. However, if parts of the disc are optically thick at sub-mm wavelengths, the sub-mm fluxes will underestimate the disc mass, and the disc's actual mass may be substantially larger, potentially sufficient to be self-gravitating.

We investigate this possibility using simple self-gravitating disc models. To match the observed mass accretion rates requires a disc-to-star mass ratio of at least  $\sim 0.5$ , which produces sub-mm fluxes that are similar to those observed for L1527 IRS in the absence of irradiation from the envelope or central star. If irradiation is significant, then the predicted fluxes exceed the observed fluxes by around an order of magnitude. Our model also indicates that the stresses produced by the gravitational instability are low enough to prevent disc fragmentation.

As such, we conclude that observations do not rule out the possibility that the disc around L1527 IRS is self-gravitating, but it is more likely that despite being a very young system, this disc may already have left the self-gravitating phase.

**Key words:** planets and satellites: formation – protoplanetary discs – planetary systems – stars: pre-main-sequence.

## 1 INTRODUCTION

It is now generally accepted that low-mass stars form through the collapse of cold, dense molecular cloud cores (Terebey, Shu & Cassen 1984). These cores, however, typically have rotation rates that mean that all the mass cannot fall directly on to the young protostar (Caselli et al. 2002). A mechanism is therefore required to transport this excess angular momentum away, allowing mass accretion to take place.

The standard scenario is that a large fraction of the material will fall on to a disc around the young protostar, and that this disc will provide the mechanism for transporting the angular momentum outwards. In many astrophysical discs, this angular momentum transport could be driven by magnetohydrodynamic (MHD) turbulence initiated by the magnetorotational instability (MRI; Balbus & Hawley 1991). At very early times, these cold, dense molecular cloud cores are, however, unlikely to be sufficiently ionized to sustain MHD turbulence (Blaes & Balbus 1994). Instead, it is thought that these discs could be massive and that disc self-gravity could provide the dominant transport mechanism during the earliest stages of star formation (Toomre 1964; Lin & Papaloizou 1986; Laughlin & Bodenheimer 1994).

Although discs around very young (Class 0 and Class I) protostars could be massive, they are difficult to identify because they are still heavily embedded in their nascent molecular cloud cores. Typically, high-resolution interferometric observations at sub-mm and mm wavelengths are used to resolve out the surrounding envelope (Eisner et al. 2005; Rodriguez et al. 2005). In some cases, these discs do appear to be quite massive (see, for example, Greaves & Rice 2011 and references therein). Interferometric observations by Maury et al. (2010) at 1.3 mm, however, suggest that discs around very young protostars are very compact ( $< 30$  au). MHD simulations of collapsing molecular cloud cores (Hennebelle & Teyssier 2008) suggest that even moderate magnetic fields can strongly influence angular momentum transport, and can prevent the disc becoming extended at these early times. This may imply that disc self-gravity is not particularly important at this stage.

By contrast, recent observations of the protostar L1527 IRS (Tobin et al. 2012) have revealed an edge-on disc with an outer radius of at least 100 au. Since this disc is edge-on, they were able to determine the rotational velocity of the material in the disc and could confirm that it was indeed in Keplerian rotation about a central protostar, with a mass of  $\sim 0.2 M_{\odot}$ . Not only is this the first confirmation of a disc around a Class 0 protostar, it also indicates that these discs can be reasonably extended ( $> 100$  au). Observations suggest that most of the luminosity is due to accretion through the disc, giving an accretion rate of  $6.6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ . Continuum observations at 870  $\mu\text{m}$  indicate a disc mass of  $\sim 0.007 \pm 0.0007 M_{\odot}$ , about 30 times smaller than the mass of the central protostar.

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If the disc mass estimate is correct, there is insufficient mass for this disc to be self-gravitating. Angular momentum transport could then be driven by MRI. MHD simulations (Papaloizou & Nelson 2003) suggest that MRI can produce stresses resulting in a viscous  $\alpha$  (Shakura & Sunyaev 1973) of up to  $\sim \times 10^{-2}$ . The steady accretion rate in a viscous accretion disc with a reasonably low mass and with a viscous  $\alpha$  of this magnitude would typically be  $10^{-7} M_{\odot} \text{ yr}^{-1}$  (Armitage, Clarke & Palla 2003). This leaves two possibilities:

- (i) this disc maintains a high accretion rate due to vigorous MRI activity supplying angular momentum transport, or
- (ii) the disc maintains a high accretion rate due to the gravitational instability, and the disc mass is higher than observations indicate.

There is both theoretical and observational evidence (Hartmann 2008; Vorobyov 2009) that disc masses around young protostars have been systematically underestimated, so option (ii) may not be particularly surprising. If the disc mass is indeed higher than estimated, disc self-gravity could then become a viable mechanism for transporting angular momentum. As self-gravitating discs tend to be more centrally condensed than their non-self-gravitating counterparts (Clarke 2009; Rice & Armitage 2009; Rice, Mayo & Armitage 2010), this provides a satisfying explanation for their ability to hide mass at high optical depths in the hotter inner disc regions.

In this paper, we determine the properties of a self-gravitating disc that could provide the observed accretion rate of L1527 IRS, and compare the observational signatures of such a disc with those observed.

## 2 MODEL

Here, we use the model developed by Clarke (2009) (see also Rice & Armitage 2009). A disc is susceptible to the gravitational instability if the  $Q$  parameter (Toomre 1964) is close to, but larger than, unity. Here, we assume that at all radii in the disc

$$Q = \frac{c_s \Omega}{\pi G \Sigma} = 2, \quad (1)$$

where  $c_s$  is the sound speed,  $\Omega$  is the angular frequency,  $G$  is gravitational constant and  $\Sigma$  is the disc surface density. It is now known that the angular momentum transport in a quasi-steady self-gravitating disc can be regarded as viscous-like (Balbus & Papaloizou 1999; Lodato & Rice 2004) such that the stresses produce an effective viscous  $\alpha$ . The mass accretion rate,  $\dot{M}$ , in such a quasi-steady disc will satisfy

$$\dot{M} = \frac{3\pi\alpha c_s^2 \Sigma}{\Omega} = \text{constant}. \quad (2)$$

The local effective gravitational  $\alpha$  is determined by assuming the disc is in thermal equilibrium (Gammie 2001), giving

$$\alpha = \frac{4}{9\gamma(\gamma - 1)t_{\text{cool}}\Omega}. \quad (3)$$

Using Rosseland mean opacities,  $\kappa$ , from Bell & Lin (1994) the optical depth can be estimated as  $\tau = \kappa \Sigma$  and the cooling rate is then (Hubeny 1990)

$$\Lambda = \frac{8\sigma T^4}{3\tau}, \quad (4)$$

where  $T$  is the mid-plane temperature and  $\sigma$  is the Stefan–Boltzmann constant. The cooling time is then the thermal energy per unit area ( $c_s^2 \Sigma / \gamma(\gamma - 1)$ ) divided by this cooling rate. This is then sufficient

to determine – given  $\dot{M}$  and stellar mass,  $M_*$  – the sound speed and surface density at any radius in a quasi-steady, self-gravitating disc.

If the disc is subject to irradiation, we modify equation (4) as follows:

$$\Lambda = \frac{8\sigma (T^4 - T_{\text{irr}}^4)}{3\tau}, \quad (5)$$

where  $T_{\text{irr}}$  represents the temperature of the local radiation field.

## 3 RESULTS

The rotational velocity of the material in the disc around L1527 IRS suggest a central protostar mass of  $\sim 0.2 M_{\odot}$  (Tobin et al. 2012). We use the above model to determine the properties of quasi-steady, self-gravitating discs around a central protostar of mass  $0.2 M_{\odot}$ . We consider two cases: in the first case, there is no significant external irradiation; in the second, we model the irradiation field from the envelope and central star as  $T_{\text{irr}} = 30 \text{ K}$ , in keeping with the dust temperature estimates of Tobin et al. (2012).

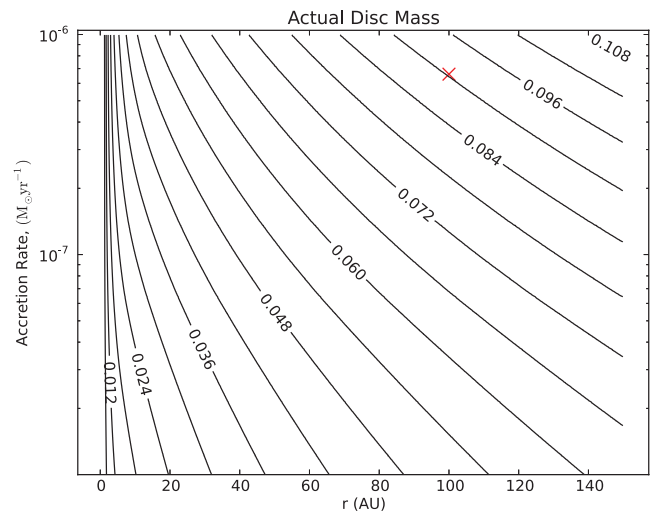
### 3.1 No irradiation

#### 3.1.1 Basic disc properties

As discussed in Section 2, given  $\dot{M}$  and  $M_*$ , we can determine the surface density and temperature at any radius in a quasi-steady, self-gravitating disc. Fig. 1 shows contours of disc mass (in  $M_{\odot}$ ) plotted against accretion rate and outer disc radius. The observed accretion rate in L1527 IRS is  $\sim 6.6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  which, if the outer radius is 100 au, would require a disc with a mass of  $0.091 M_{\odot}$ . This is shown by the red cross in Fig. 1. If the outer radius is 150 au, this rises to  $\sim 0.11 M_{\odot}$ . This is about half the mass of the central star and more than 10 times greater than that estimated from the observed  $870 \mu\text{m}$  flux from L1527 IRS.

#### 3.1.2 Mass estimates

We can use our models to determine the  $870 \mu\text{m}$  flux for our simulated discs. For a system at a distance  $D$ , the flux at frequency  $\nu$



**Figure 1.** 2D contours of the actual disc mass calculated from the self-gravitating disc models, as a function of the steady state accretion rate  $\dot{M}$ , and the disc's outer radius  $r_{\text{out}}$ , for a star of mass  $0.2 M_{\odot}$ . The red cross indicates the required disc mass, assuming an outer radius of 100 au, to produce a mass accretion rate like that measured for L1527 IRS.

from an annulus of the disc at radius  $r$  from the central star, and with radial extent  $dr$  is

$$F_\nu(r) dr = \frac{2k}{c^2 D^2} v^2 \kappa(\nu) \Sigma(r) T(r) 2\pi r dr, \quad (6)$$

where  $k$  is Boltzmann's constant,  $c$  is the speed of light and  $T(r)$  is the disc mid-plane temperature. The frequency dependent opacity  $\kappa(\nu)$  is

$$\kappa(\nu) = \kappa_0 \left( \frac{\nu}{\nu_0} \right)^\beta = \kappa_0 \left( \frac{\lambda_0}{\lambda} \right)^\beta, \quad (7)$$

where  $\beta$  is typically 1 and  $\kappa_0$  is the opacity at a reference wavelength of  $\lambda_0 = 850 \mu\text{m}$ .

Quasi-steady, self-gravitating discs are, however, centrally condensed (Clarke 2009; Rice & Armitage 2009) and it is expected that they may be optically thick even at mm wavelengths (Greaves & Rice 2010). We account for optically thick regions ( $\tau(r, \nu) = \Sigma(r)\kappa(\nu) > 1$ ) by modifying equation (6) as follows

$$F_\nu(r) dr = \begin{cases} \frac{2k}{c^2 D^2} v^2 \kappa(\nu) \Sigma(r) T(r) 2\pi r dr & \tau \leq 1 \\ \frac{2k}{c^2 D^2} v^2 \frac{T(r)}{\tau^{1/4}} 2\pi r dr & \tau > 1. \end{cases} \quad (8)$$

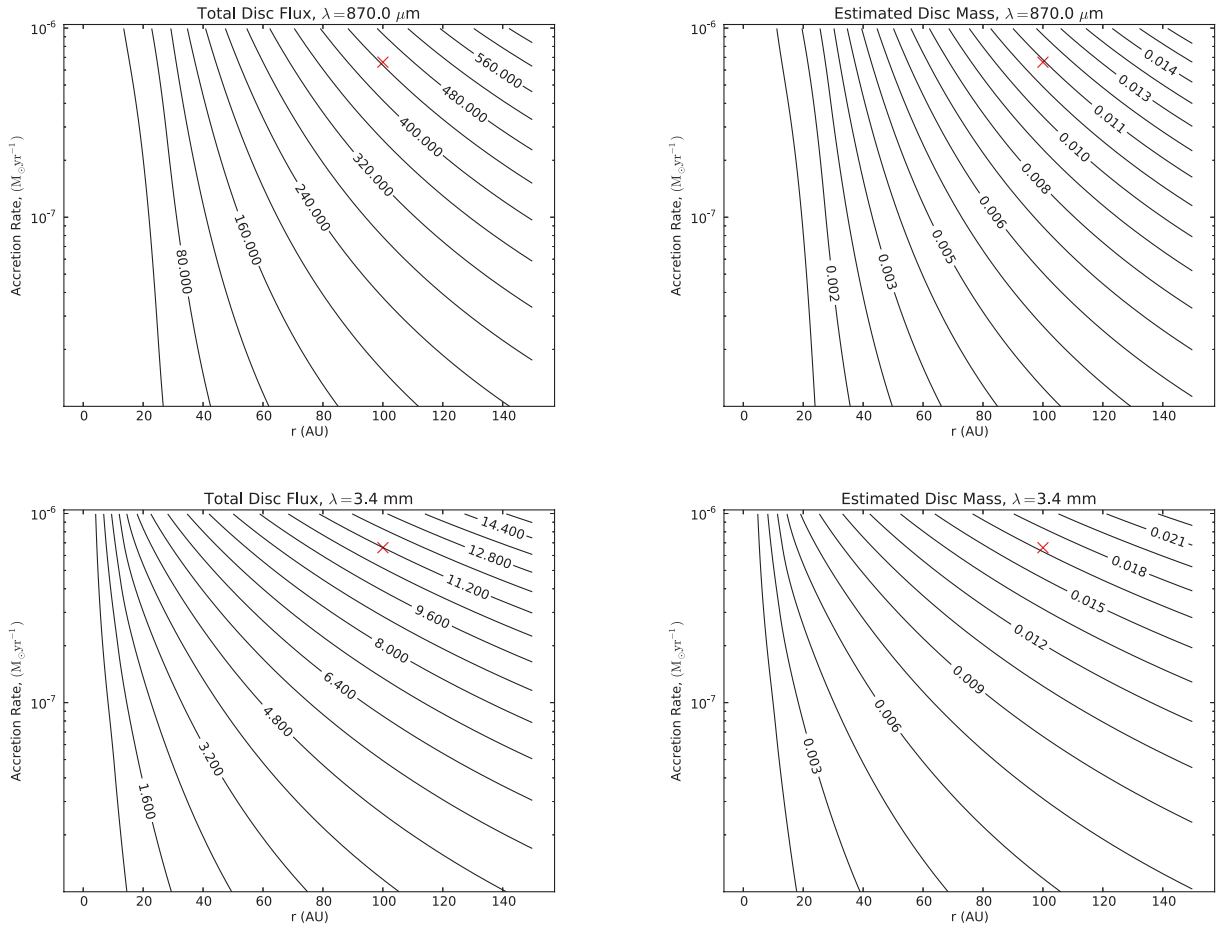
To calculate the integrated flux at  $870 \mu\text{m}$  from our simulated discs, we simply integrate equation (8) from the inner disc edge ( $r = 1 \text{ au}$ ) to the outer disc radius, using  $\kappa_0 = 0.035 \text{ cm}^2 \text{ g}^{-1}$  and  $\beta = 1$ .

The top-left panel of Fig. 2 shows contours of  $870 \mu\text{m}$  flux in mJy plotted against  $\dot{M}$  and outer disc radius,  $r_{\text{out}}$ . For  $r_{\text{out}} = 100 \text{ au}$  and for  $\dot{M} = 6.6 \times 10^{-7} \text{ M}_\odot \text{ yr}^{-1}$ , the  $870 \mu\text{m}$  flux is  $\sim 475 \text{ mJy}$ . For  $r_{\text{out}} = 150 \text{ au}$ , this increases to  $650 \text{ mJy}$ . The observed  $870 \mu\text{m}$  flux for L1527 IRS is  $213.6 \pm 8.1 \text{ mJy}$ . Despite our required disc masses (shown in Fig. 1) being an order of magnitude – or more – greater than that determined for L1527 IRS, the  $870 \mu\text{m}$  flux is only a factor of 2–3 greater than that observed. Our calculation is also fairly simple and essentially assumes a face-on geometry. The disc in L1527 IRS is edge-on and one might expect a reduction in flux at these wavelengths by as much as a factor of  $\sim 2$  due to this edge-on geometry (e.g., Whitney et al. 2003).

Typically, the disc mass is inferred from the long-wavelength flux using

$$M_{\text{disc}} = \frac{D^2 F_\nu c^2}{2\kappa(\nu) k v^2 T_{\text{dust}}}. \quad (9)$$

Although our models have self-consistent disc temperatures, to compare with the results of Tobin et al. (2012), we use their value of  $T_{\text{dust}} = 30 \text{ K}$ . The top-right panel of Fig. 2 shows the disc mass that



**Figure 2.** 2D contours of the self-gravitating disc models observable properties, as a function of the steady-state accretion rate  $\dot{M}$  and the disc's outer radius  $r_{\text{out}}$ , for a star of mass  $0.2 \text{ M}_\odot$ , assuming no external irradiation. Top left: the  $870 \mu\text{m}$  flux (in mJy); top right, the disc mass (in  $\text{M}_\odot$ ) estimated from the  $870 \mu\text{m}$  flux; bottom left, the  $3.4 \text{ mm}$  flux (in mJy); bottom right, the disc mass (in  $\text{M}_\odot$ ) estimated from the  $3.4 \text{ mm}$  flux. Assuming an outer radius of  $100 \text{ au}$ , the red crosses indicate what would be expected for a disc with an accretion rate similar to that of L1527 IRS.

would be inferred from our simulated 870  $\mu\text{m}$  flux. As expected, for  $r_{\text{out}} = 100 \text{ au}$  and  $\dot{M} = 6.6 \times 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$ , the 870  $\mu\text{m}$  flux would suggest a disc mass of  $\sim 0.011 \text{ M}_{\odot}$ , almost 10 times lower than the actual disc mass. Admittedly, if one compares the top-left and -right panels of Fig. 2 one will notice that our estimate of the disc mass for a flux of 213 mJy is slightly less than that determined by Tobin et al. (2012) ( $0.00525 \text{ M}_{\odot}$  rather than  $0.007 \text{ M}_{\odot}$ ), but this does not really change our main result. Using the 870  $\mu\text{m}$  flux, the mass one would estimate for a self-gravitating disc accreting at  $6.6 \times 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$  around a star of  $M_* = 0.2 \text{ M}_{\odot}$  would be 5–10 times lower than the actual disc mass and only 2–3 times higher than that estimated for the disc around L1527 IRS.

Tobin et al. (2012) also measure 3.4 mm fluxes which they find to be  $16.0 \pm 1.4 \text{ mJy}$ . Assuming  $\beta = 1$  in equation (7), we can calculate the 3.4 mm fluxes from our disc models. This is shown in the bottom-left panel of Fig. 2. For a disc of radius  $r_{\text{out}} = 100 \text{ au}$  and for  $\dot{M} = 6.6 \times 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$ , our model predicts a 3.4 mm flux of  $\sim 11.1 \text{ mJy}$ . This is lower than, but similar to, that determined for L1527 IRS.

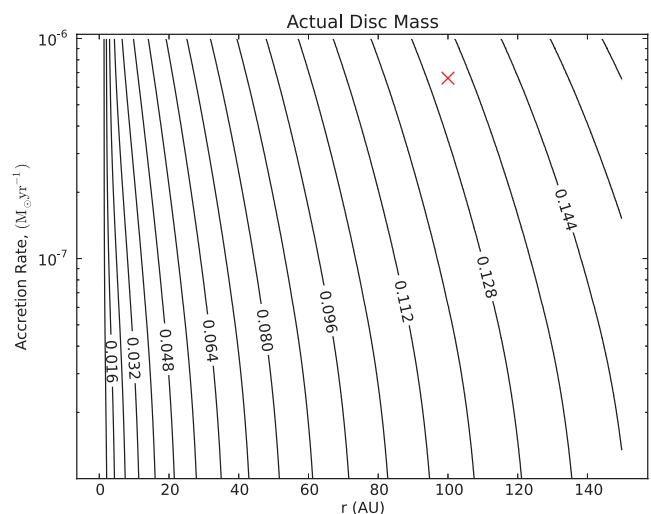
We can again estimate the disc mass using equation (9) which is shown in the bottom-right panel of Fig. 2. Our simulated 3.4 mm flux would suggest a disc mass (for properties similar to the of L1527 IRS) of  $0.018 \text{ M}_{\odot}$ . This is higher than the 870  $\mu\text{m}$  flux estimate ( $0.011 \text{ M}_{\odot}$ ) indicating that, at longer wavelengths, the disc is less optically thick. The difference is, however, much smaller than that seen by Tobin et al. (2012). Their disc mass estimated from the 3.4 mm flux ( $0.025 \pm 0.003 \text{ M}_{\odot}$ ) is 3.6 times greater than the 870  $\mu\text{m}$  estimate. They have more confidence in the 870  $\mu\text{m}$  flux as it is less affected by assumption of  $\beta$  but do suggest that this could indicate the disc being optically thick at 870  $\mu\text{m}$ , but our results would suggest that this alone cannot explain the observed difference the 870  $\mu\text{m}$  and 3.4 mm fluxes. We have assumed  $\beta = 1$ , reflecting the current uncertainty regarding grain growth, and the degeneracy between  $\beta$  and the disc mass when interpreting observations (Andrews & Williams 2005).

We therefore also considered what would happen if we varied  $\beta$ . For  $\beta = 0.6$ , we find that the 3.4 mm flux (at  $\dot{M} = 6.6 \times 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$  and  $r_{\text{out}} = 100 \text{ au}$ ) increases from  $\sim 11 \text{ mJy}$  (when  $\beta = 1$ ) to  $\sim 16 \text{ mJy}$ . If one then assumes  $\beta = 1$  when determining the disc mass from this flux, this increases the estimated disc mass from  $0.018$  to  $0.026 \text{ M}_{\odot}$ . The large difference in the measured 870  $\mu\text{m}$  and 3.4 mm fluxes could, therefore, indicate that some grain growth has taken place. If so, this could also suggest that such discs would still have optically thick regions even at mm wavelengths.

### 3.2 Irradiation at $T_{\text{irr}} = 30 \text{ K}$

In the absence of external irradiation, the gravitational instability generates temperatures in the outer disc much lower than those estimated by Tobin et al. (2012). If we add external irradiation to ensure the outer disc cannot cool below 30 K, how does this affect the disc properties and the observable flux and mass?

Fig. 3 shows the actual disc mass as a function of  $\dot{M}$  and  $r_{\text{out}}$  in the presence of irradiation. As irradiation tends to weaken the gravitational instability, the disc itself must be more massive for a given  $\dot{M}$ – $r$  locus to maintain a marginally unstable state (Cai et al. 2008; Kratter & Murray-Clay 2011; Rice et al. 2011; Forgan & Rice 2013). This would push the actual disc mass of L1527 IRS to  $0.132 \text{ M}_{\odot}$ , around two-thirds the mass of the central star. The contours are almost vertical, indicating that the disc surface density profile is almost independent of accretion rate, and depends only on radius. This is suggestive of heating due to the gravitational



**Figure 3.** 2D contours of the actual disc mass calculated from self-gravitating disc models in an external irradiation field of  $T_{\text{irr}} = 30 \text{ K}$ , as a function of the steady state accretion rate  $\dot{M}$ , and the disc’s outer radius  $r_{\text{out}}$ , for a star of mass  $0.2 \text{ M}_{\odot}$ . The red cross indicates the required disc mass, assuming an outer radius of 100 au, to produce a mass accretion rate like that measured for L1527 IRS.

instability being superseded by the heating due to the irradiation, and the subsequent weakening of the instability, which occurs even at such large disc-to-star mass ratios (Rice & Armitage 2009). As such, the disc surface density profile is no longer as centrally condensed as it was in the non-irradiated case.

Adding this extra mass to the disc’s outer regions boosts the observed flux by around a factor of 5 (left-hand panels of Fig. 4). As the dust mass depends linearly on the flux, the estimated mass is also a factor of 5 larger (right-hand panels of Fig. 4).

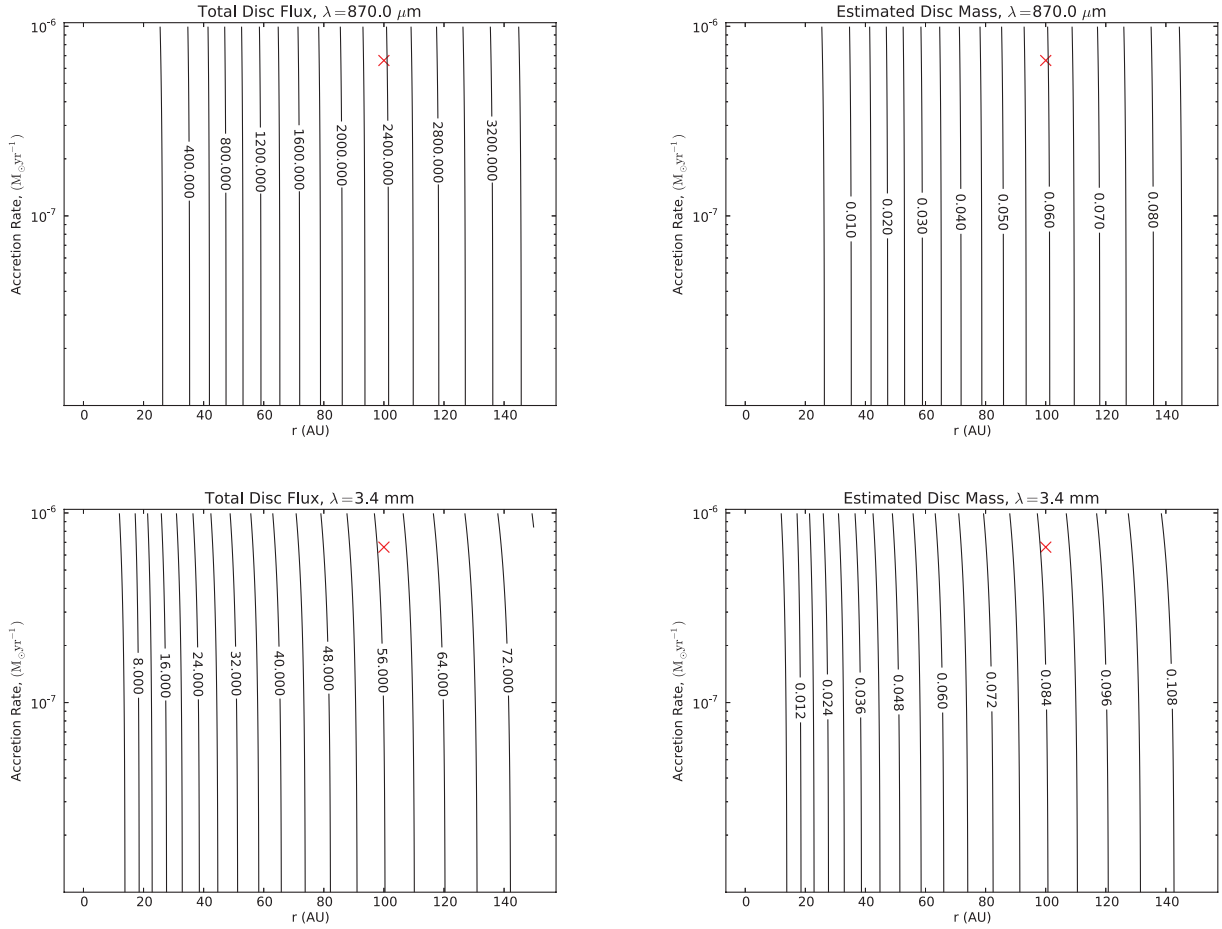
This is certainly less attuned with the observed flux than the non-irradiated case. The uncertainty regarding the temperature profile of L1527 IRS leaves us uncertain as to the efficacy of self-gravitating disc models to explain the observations. While it is likely that irradiation does set the temperature of the outer disc, modelling of other dust discs in Taurus in the sub-mm suggests that the disc temperature at 100 au could be up to a factor of 3 lower (Andrews & Williams 2005).

### 3.3 Fragmentation

Although we have primarily considered quasi-steady self-gravitating discs, it is thought that if such discs are sufficiently unstable they may undergo fragmentation to form bound objects (Gammie 2001; Rice et al. 2003). This depends on how quickly such discs are able to cool and it is expected that it would only be possible in the outer parts of such discs (Rafikov 2005; Stamatellos, Hubber & Whitworth 2007). The condition for fragmentation is that the effective gravitational viscosity satisfies  $\alpha > 0.06$  (Rice, Lodato & Armitage 2005). Forgan & Rice (2011) suggest that once  $\alpha$  exceeds this threshold, fragmentation also requires that the Jeans mass changes sufficiently rapidly that a clump would actually form on a reasonably short time-scale. This allows one to estimate under what conditions fragmentation should occur and, if fragmentation does occur, the resulting Jeans mass.

In the non-irradiated case, our calculation show that L1527 IRS would need to maintain an accretion rate of around  $\dot{M} \sim 8 \times 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$  or higher to fragment, and is therefore extremely





**Figure 4.** 2D contours of the self-gravitating disc models observable properties, as a function of the steady-state accretion rate  $\dot{M}$  and the disc’s outer radius  $r_{\text{out}}$ , for a star of mass  $0.2 M_{\odot}$ , assuming irradiation with a uniform temperature of  $T_{\text{irr}} = 30$  K. Top left: the  $870 \mu\text{m}$  flux (in mJy); top right, the disc mass (in  $M_{\odot}$ ) estimated from the  $870 \mu\text{m}$  flux; bottom left, the  $3.4 \text{ mm}$  flux (in mJy); bottom right, the disc mass (in  $M_{\odot}$ ) estimated from the  $3.4 \text{ mm}$  flux. Assuming an outer radius of 100 au, the red crosses indicate what would be expected for a disc with an accretion rate similar to that of L1527 IRS.

close to fragmenting. In the presence of irradiation, this critical accretion rate increases, and the disc is therefore stable (Forgan & Rice 2013). It is therefore probable that L1527 IRS will not fragment but if fragmentation has occurred, it may be possible to detect enhanced emission consistent with an object of a few Jupiter masses or larger forming via fragmentation in such a disc (Greaves et al. 2008).

#### 4 DISCUSSION AND CONCLUSION

The observation of a rotationally supported disc in the L1527 IRS protostellar system is the first confirmation of a reasonably extended ( $r_{\text{out}} > 100 \text{ au}$ ) disc around a Class 0 protostar. The disc mass estimated from the sub-mm flux, if correct, suggests that such a disc cannot be self-gravitating.

We show here, that a self-gravitating disc can provide the observed mass accretion rate, but the disc mass would need to be at least an order of magnitude greater than that observed. Such discs are very centrally condensed (Clarke 2009; Rice & Armitage 2009) and so the inner regions are optically thick even at long wavelengths. Such discs may produce episodic outbursts (Vorobyov & Basu 2005, 2010) and the observed FU Orionis outbursts (Hartmann & Kenyon

1996) may be driven by centrally condensed self-gravitating discs (Zhu, Hartmann & Gammie 2009; Zhu et al. 2010).

Using reasonable values for the frequency-dependent opacity, we show that the fluxes produced by the model are similar to that observed for L1527 IRS if external irradiation is weak. If these fluxes are then used to estimate the disc mass, these would give estimates 5–10 times lower than the actual disc mass. By varying the opacity spectral index  $\beta$  from its canonical value of 1 down to 0.6, the fluxes obtained from the model match the observed values very closely. This might suggest that significant grain growth is already underway in the Class 0 phase, perhaps due to the self-gravitating disc turbulence reducing the relative grain velocities allowing the grain growth process to be accelerated (Rice et al. 2004; Clarke & Lodato 2009). Such a hypothesis remains unconfirmable due to the degeneracies tying  $\beta$  to the disc mass, not to mention the underlying uncertainties surrounding the grain composition and size distribution (Andrews & Williams 2005 and references therein).

However, in the presence of irradiation, the self-gravitating disc model produces fluxes up to five times higher than observed. We therefore cannot claim that the observations of L1527 IRS show that the disc is massive and self-gravitating, especially as we do not model obscuration from the envelope in which the system is embedded. If the envelope strongly obscures flux over a wide range

of wavelengths, then the overestimated flux produced by the disc models in the irradiated case may be greatly reduced, bringing them closer to the observed fluxes from L1527 IRS.

Equally, given the extremely young age of the system and the difficulties of modelling the disc in the presence of irradiation, we can infer that the self-gravitating phase of protostellar discs is indeed constrained to the very earliest stages of star formation. Despite possessing a high accretion rate, the self-gravitating disc model's overestimate of flux in the presence of irradiation suggests that the disc may already have transitioned from a state in which self-gravity dominates as an angular momentum transport mode, to a state where MRI now dominates the transport. If this is true, and the disc is still somewhat self-obscured, it is evident that self-gravity becomes ineffective in protostellar discs even while the disc-to-star mass ratio remains quite large (Rice & Armitage 2009). This is illustrated by the disc mass becoming only weakly dependent on accretion rate in the presence of irradiation, i.e. they are not strongly centrally condensed, and are in fact more akin to the typical  $\Sigma \propto r^{-1}$  power-law disc profiles. We suggest that the actual disc mass lies between the lower limit (established by observation) of  $0.007 \pm 0.0007 M_{\odot}$  and the upper limit (established by this work) of  $\sim 0.1 M_{\odot}$ .

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